Collaboratory for the Study of Earthquake Predictability (CSEP)

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Presentation to the National Earthquake Prediction Evaluation Council

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Collaboratory for the Study of Earthquake Predictability (CSEP)

Project Summary

- Earthquake prediction research is hampered by inadequate infrastructure for conducting scientific prediction experiments.
- SCEC has received $1.2 million from the W. M. Keck Foundation for a 3-yr program to develop CSEP infrastructure
  - Unique facility with the experimental standards, testing protocols, and cyberinfrastructure needed to support a geographically broad program of research on earthquake predictability
- Primary objective: rigorous *comparative* testing of diverse prediction experiments spanning a variety of fault systems that builds on the RELM program

The dialog on earthquake prediction among scientists – and between the public and the scientific community – has become corrupted by the controversies surrounding "operational" earthquake prediction.

It needs to be reconstructed…

- T. H. Jordan, "Earthquake predictability, brick by brick", *Seismol. Res. Lett.*, vol. 77, pp. 3-7, 2006

Three Definitions

- *Earthquake predictability*
  - degree to which the future occurrence of earthquakes is encoded in the behavior of an active fault system
- *Scientific earthquake prediction*
  - a testable hypothesis, usually stated in probabilistic terms, of the location, time, and size of fault ruptures
- *Useful earthquake prediction*
  - advance warning of potentially destructive fault rupture precise and reliable enough to warrant actions to prepare communities

Three Questions

Q1. How should scientific earthquake predictions be stated and tested?

- i.e., how should prediction experiments be conducted and evaluated?

Q2. What is the intrinsic predictability of the earthquake rupture process?

Q3. Can knowledge of large-earthquake predictability be deployed as useful predictions?

- i.e., is operational earthquake prediction feasible?

"Silver Bullet" Approach

- Seeks useful, short-term earthquake predictions
  - motivated by laboratory studies of rupture nucleation
  - dominated research after 1975 Haicheng earthquake
- Searches for signals diagnostic of approach to rupture, including:
  - foreshocks
  - strain precursors
  - electromagnetic precursors
  - hydrologic changes
  - animal behavior
- Has not thus far led to useful prediction methodologies

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Anticipating Earthquakes

High above Earth where seismic waves never reach, satellites may be able to detect earthquakes--before they strike.

"Although earthquakes seem to strike out of the blue, the furious energy that a quake releases builds up for months and years beforehand in the form of stresses within Earth's crust. At the moment, forecasters have no direct way of seeing these stresses or detecting when they reach critically high levels.

"That may be changing, however. Satellite technologies being developed at NASA and elsewhere might be able to spot the signs of an impending quake days or weeks before it strikes, giving the public and emergency planners time to prepare." **[i.e., might answer Q3]**

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"Brick-by-Brick" Approach

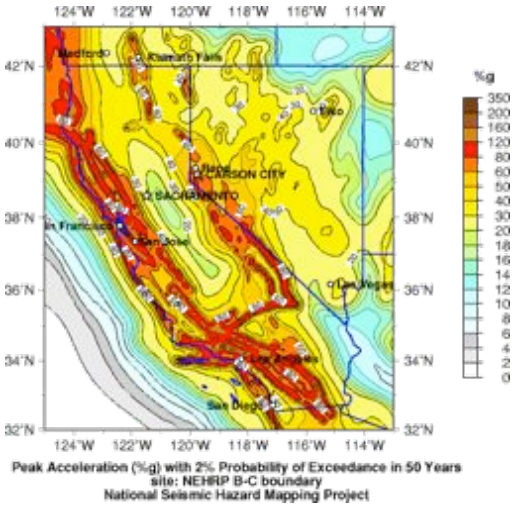
- Focused on experimentation (*Q1*) and predictability (*Q2*), not operational prediction (*Q3*)
- Built on system-specific models of stress transfer and earthquake triggering
  - Probabilistic prediction of earthquakes on multiple time scales, incorporating geologic and geodetic information, as well as seismicity data
  - Steady efforts to understand and improve predictability, even if probability gains are small
- Demonstrates predictability by rigorous testing based on intercomparison of algorithms
  - RELM program and its extension to a *Collaboratory for the Study of Earthquake Predictability* (CSEP)

Types of Earthquake Prediction

- Prediction vs. Forecasting
  - Predictions attempt to identify periods of increased probability relative to long-term (say, $G > 10$)
- Time scale of prediction
  - Long-term (decades to centuries) ⇒ forecasts
  - Intermediate-term (months to years)
  - Short-term (seconds to weeks)
- Input basis
  - Data-based
  - Model-based
- Output basis
  - probability-based
  - alarm-based
- Retrospective vs. prospective

Official U. S. Earthquake Prediction

USGS National Seismic Hazard Mapping Project (2002)

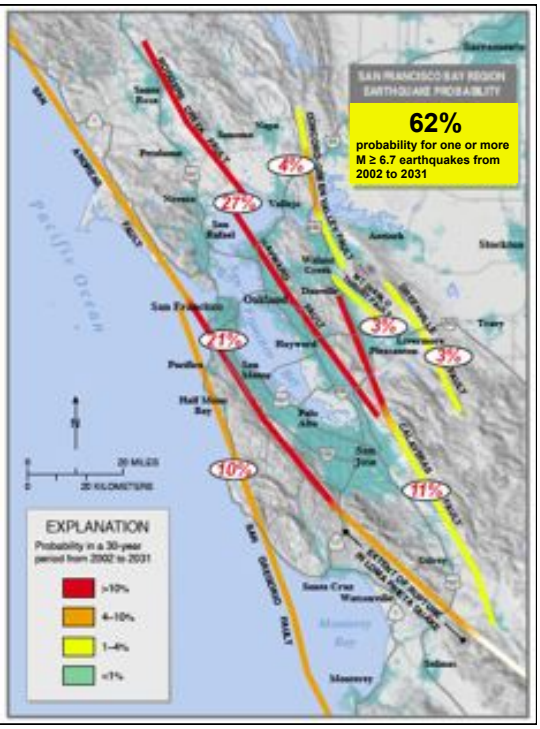


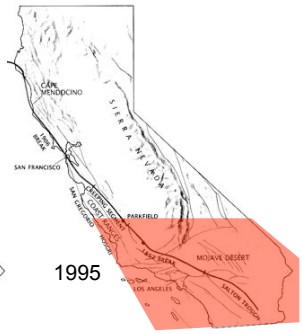
- Specifies the maximum shaking expected over a long period of time (typically 50 years)
  - at all U.S. sites
  - from all potential earthquake sources
- Rupture forecast is based on time-independent (Poisson) probabilities
- Ignores information about current state of the fault system

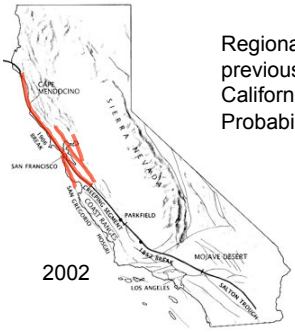
Working Group on California Earthquake Probabilities (2002)

Earthquake Probabilities in the San Francisco Bay Region: 2002–2031

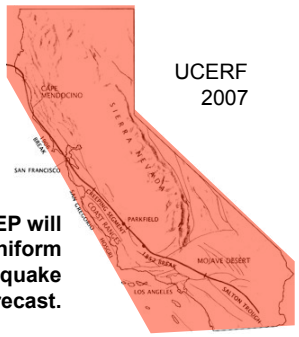
State-of-the-art time-dependent model







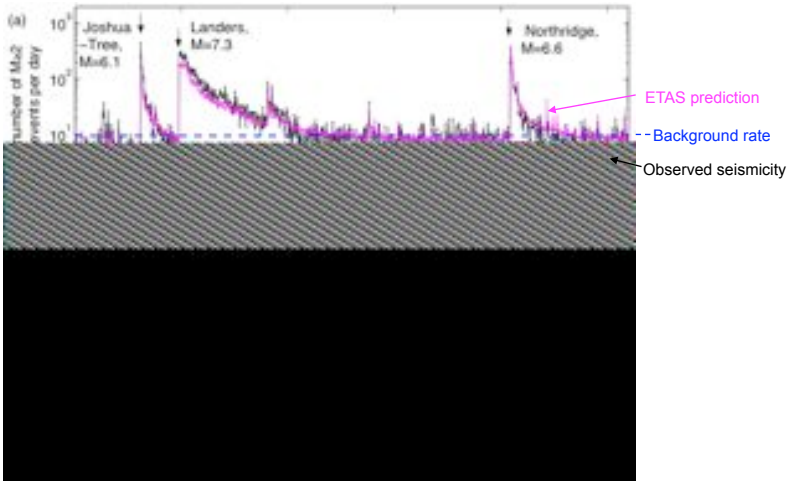
Regional forecasts by the four previous Working Groups on California Earthquake Probabilities.



UCERF 2007

The new WGCEP will develop a uniform California earthquake rupture forecast.

ETAS Prediction of Short-Term Seismicity



Retrospective daily ETAS predictions of Southern California seismicity by Helmstetter et al. (2005)

ETAS Assumptions

1. All earthquake magnitudes above a lower cutoff m_0 are independent samples of the Gutenberg-Richter probability distribution,

$$P(m) = 10^{-b(m-m_0)}$$

2. All earthquakes give birth to daughter events at an average rate

$$R(m,x,t) = \rho(m)\phi(x)\psi(t)$$

3. The triggering rate is assumed to increase exponentially with magnitude,

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been

4. decrease with distance from the mother event,

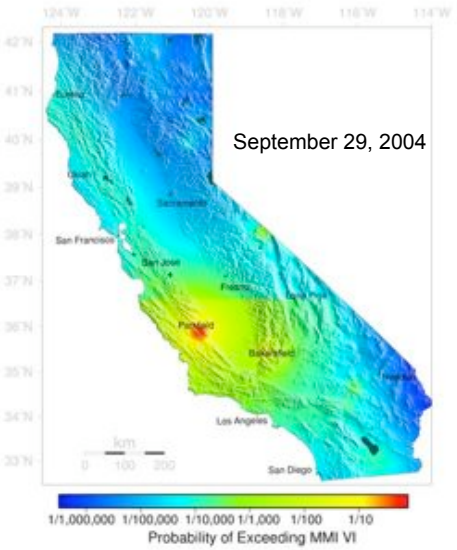
$$\phi(r) \sim (d+r)^{-q}$$

5. and decay with time according to the modified Omori law,

$$\psi(t) \sim (c+t)^{-p}$$

Short-Term Earthquake Probability (STEP) Map

Gerstenberger et al. (2005)



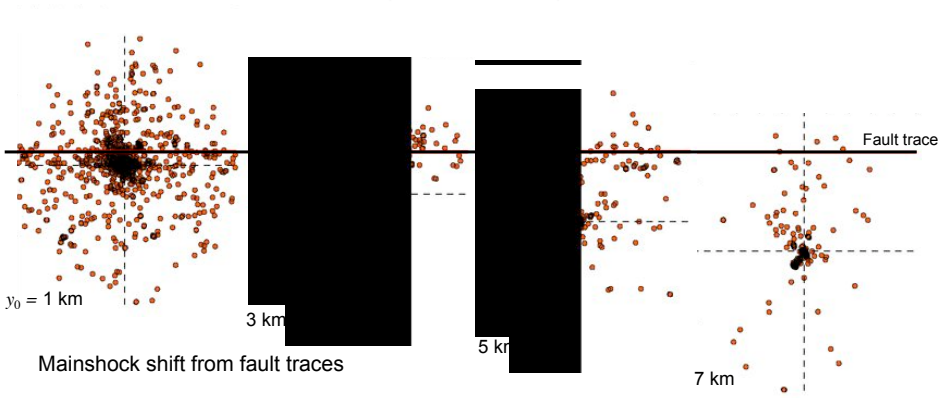
http://pasadena.wr.usgs.gov/step

Evaluation of ETAS Model

- The ETAS model provides a good first-order description of earthquake triggering
  - Suitable as a reference model for short-term predictions
- In Southern California, short-term predictions of seismicity rate based on ETAS achieve probability gain factors >10 relative to long-term Poisson models (Helmstetter et al., 2005)
  - Gain decreases rapidly with magnitude threshold; i.e., little gain for large earthquakes
  - System-specific models provide basis for improvements
- Some regions, such as ridge transform faults, show anomalous statistics -- and more predictability -- relative to ETAS
  - J. McGuire, M. Boettcher & T. H. Jordan, Foreshock sequences and short-term earthquake predictability on East-Pacific Rise transform faults, *Nature*, **434**, 457-461 (24 March 2005)

Aftershock Stacks

Shearer (2004) catalog for Southern California
(5 km ≤ *h* ≤ 15 km)



Mainshock shift from fault traces

Results suggest a modified ETAS spatial kernel of the form:

$$\phi \sim y_0^{-\gamma} r^{-q}$$

Powers & Jordan (2005)

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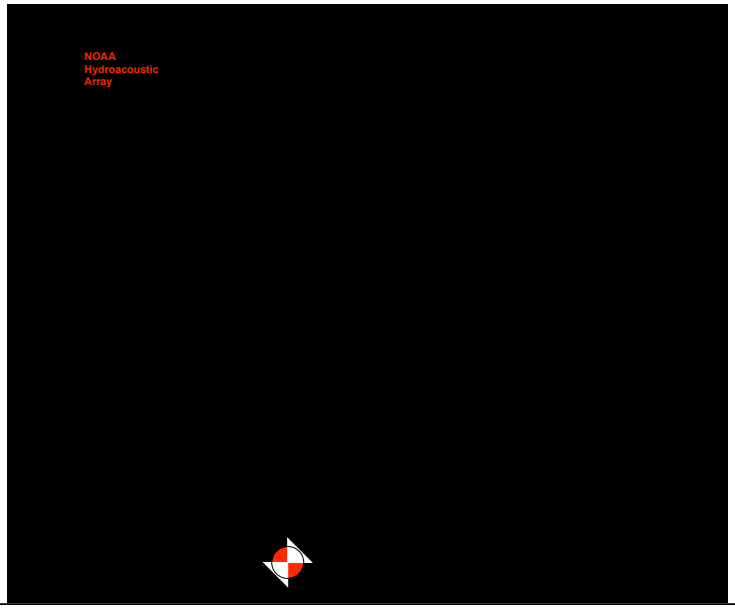
Transform Faults on East Pacific Rise

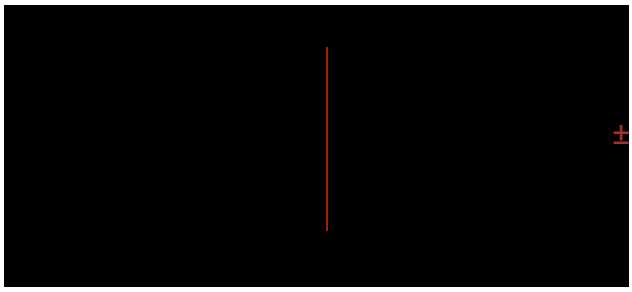


Aftershock Statistics for Ridge Transform Faults

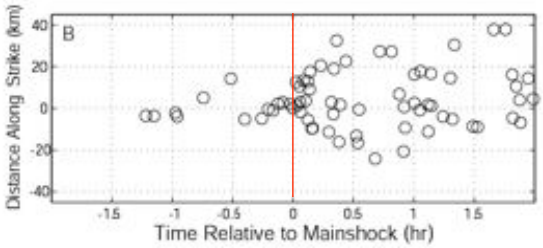
RTF aftershock sequences are very depleted compared to continental strike-slip earthquakes.

GDQ Seismicity Stacked on Mainshock Origin Times

(9 mainshocks, Mar 1996 - Nov 2001)

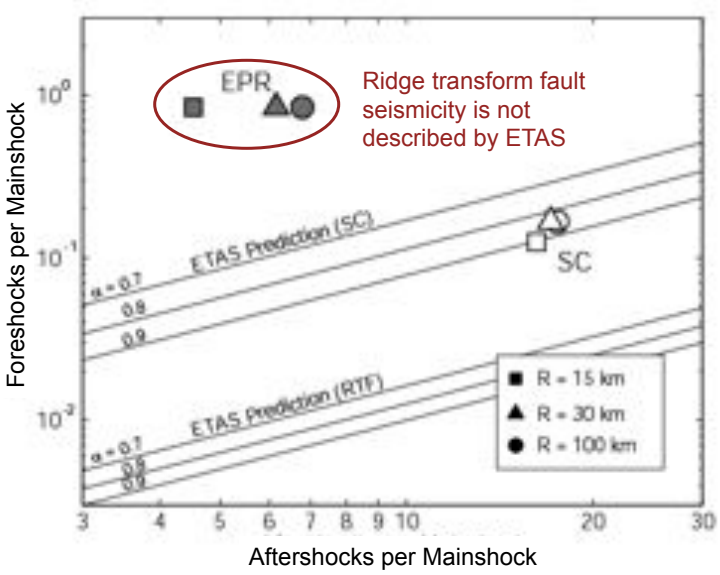


± 20 hr

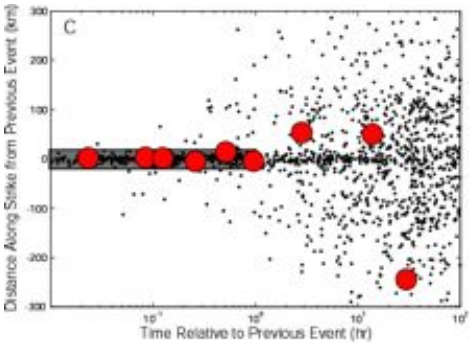


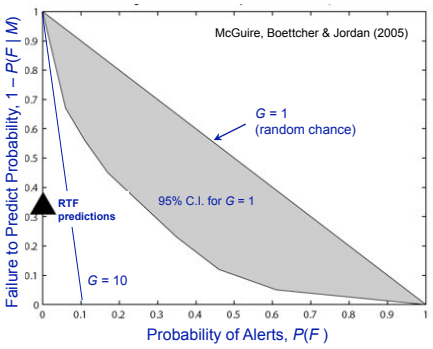
± 2 hr

Comparison of RTF Foreshock/Aftershock Statistics with ETAS Prediction



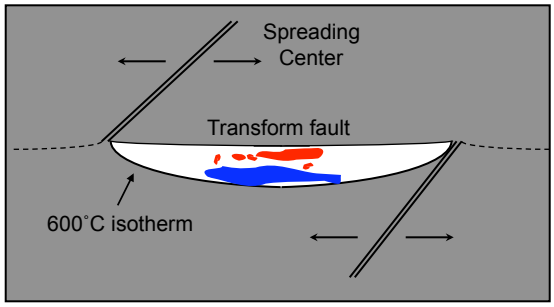
Short-Term Prediction of Large Earthquakes on GDQ Transform Faults

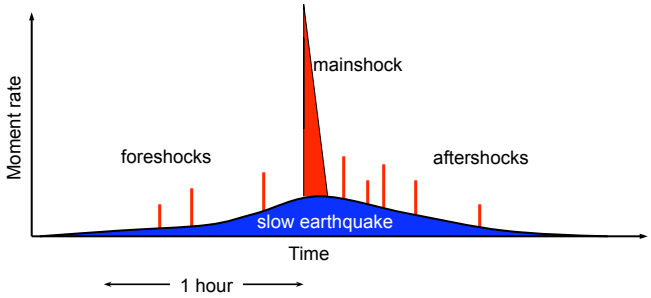


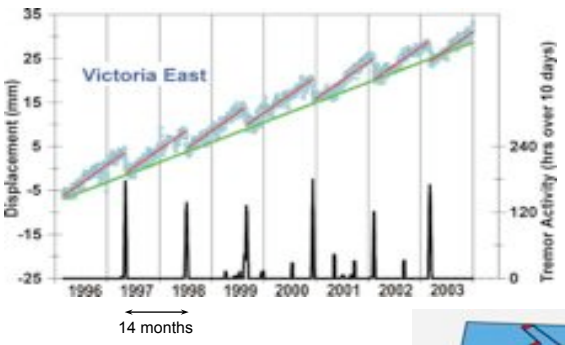


- The high rate of proximate foreshocks suggests a "naïve" scheme for short-term earthquake prediction:
  - We simply assume *every* event is a foreshock of an impending large earthquake.
- Formalization into a 4-parameter prediction algorithm:
  - For every RTF event with $m \geq m_0$, issue an alert that an earthquake $m \geq m_P$ will occur in time window of length t_P and a spatial window of radius r_P about the event's epicenter.

Slow Precursors on Oceanic Transform Faults

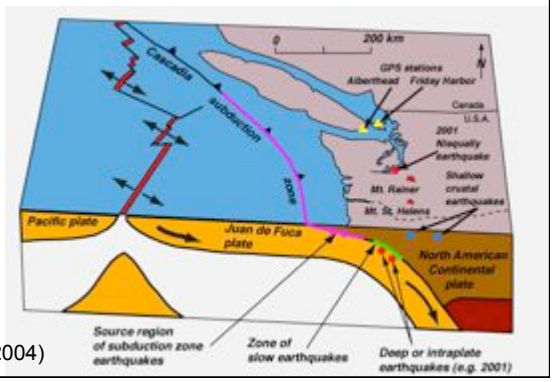






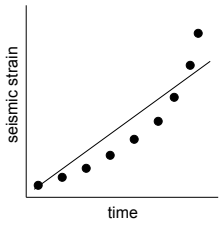
Slow Earthquakes and Deep Tremor in the Cascadia Subduction Zone

Do slow slip transients in subduction zones trigger fast ruptures?

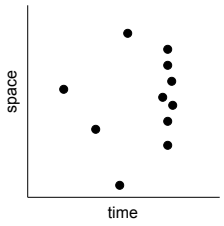


Miller (2004)

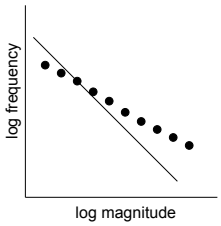
Seismicity Patterns Used in Intermediate-Term Prediction



Accelerating Seismicity

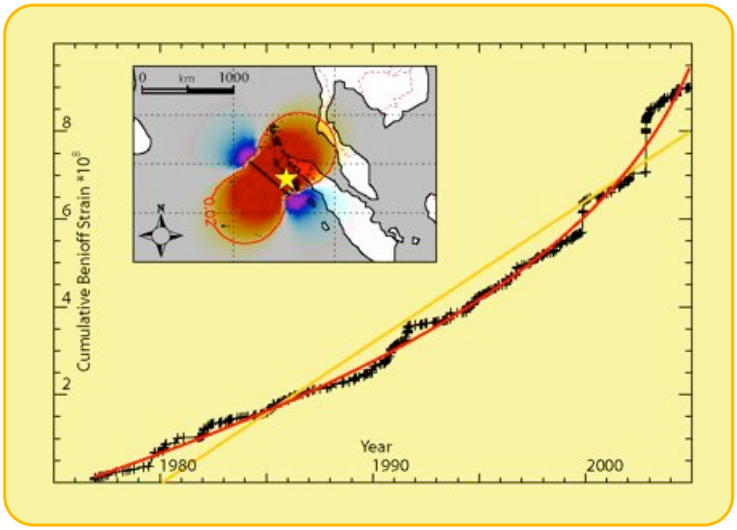


Long-Range Correlation

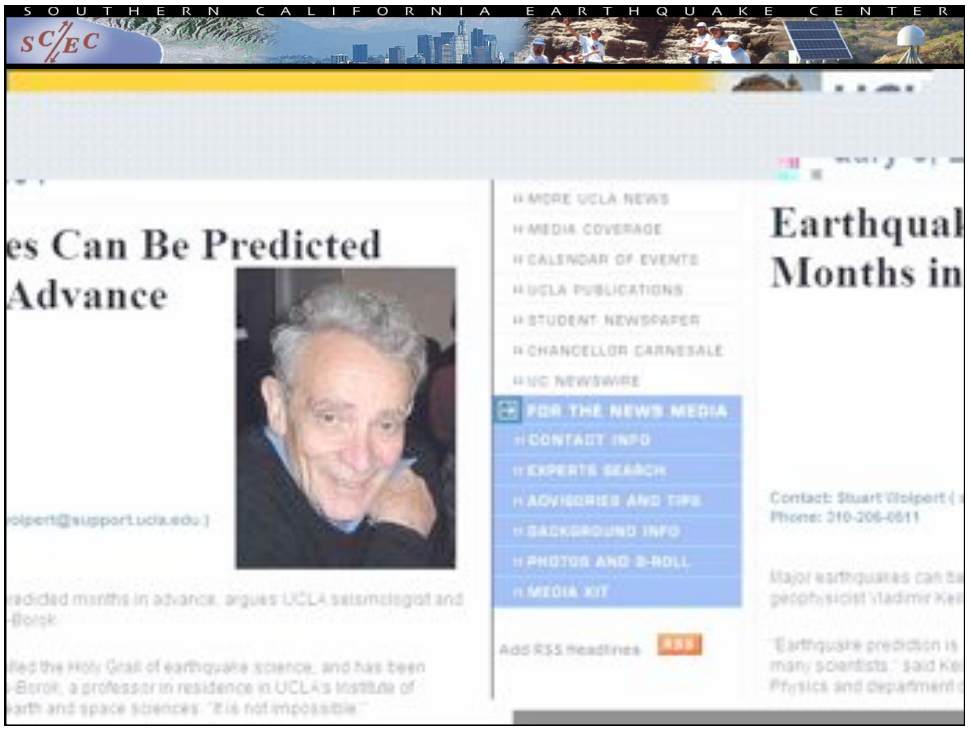


Large-Magnitude Enrichment

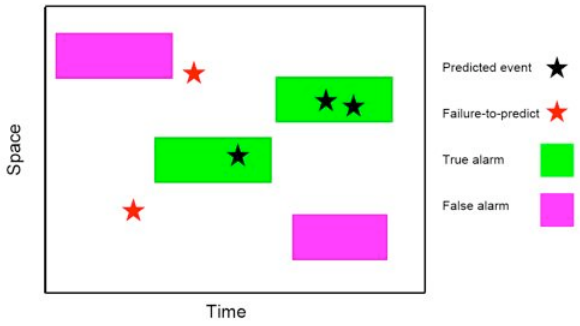
Accelerating Seismicity Before the 2004 M 9 Sumatra-Andaman Islands Earthquake



Mignan, Bowman & King, in preparation, 2005



Alarm-Based Prediction



Prediction \ Outcome	YES	NO
YES	True alarm (*a*)	False alarm (*b*)
NO	Failure-to-predict (*c*)	True non-alarm (*d*)

Contingency Table

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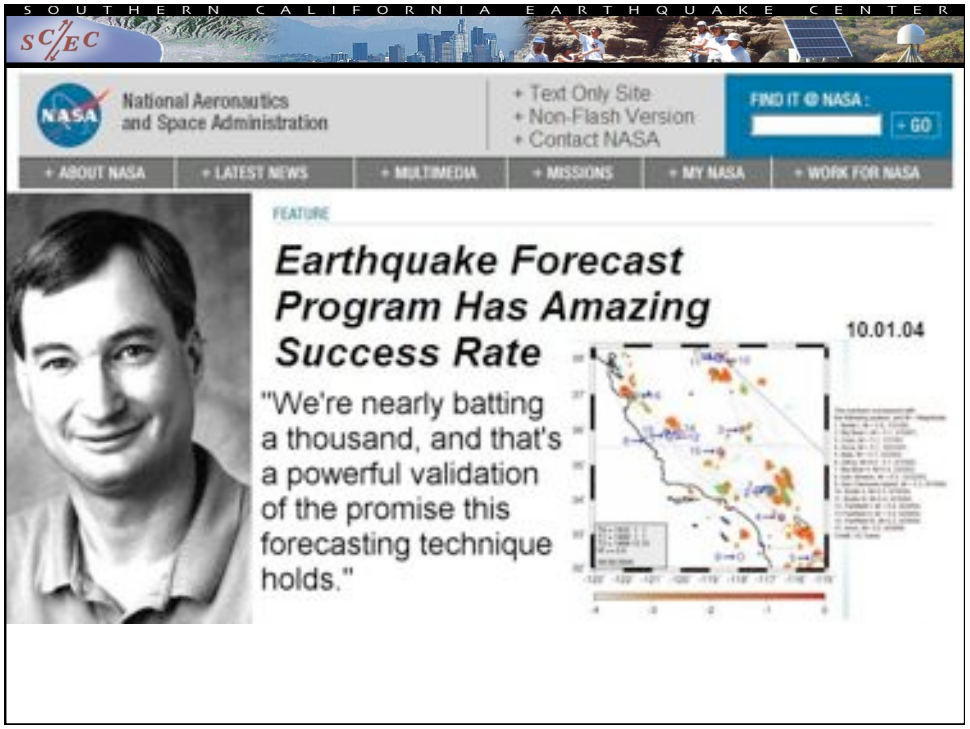
RTP Results (Dec 20, 2005)

Region	Start	End	Result
Japan	Mar 2003	Nov 2003	hit
California	May 2003	Feb 2004	hit
California	Nov 2003	Sep 2004	false alarm
Japan	Feb 2004	Nov 2004	false alarm
Italy	Feb 2004	Nov 2004	false alarm
California	Nov 2004	Aug 2005	false
California	Nov 2004	Aug 2005	
Italy	Dec 2004	Oct 2005	

Prediction \ Outcome	YES	NO
YES	2	6
NO	3	-

Date	Region	Lat	Lon	Mag
15 Jun 2005	California	41.28	-125.98	7.2 Mw
17 Jun 2005	California	40.75	-126.59	6.7 Mw
16 Aug 2005	Japan	38.16	142.11	7.2 Mw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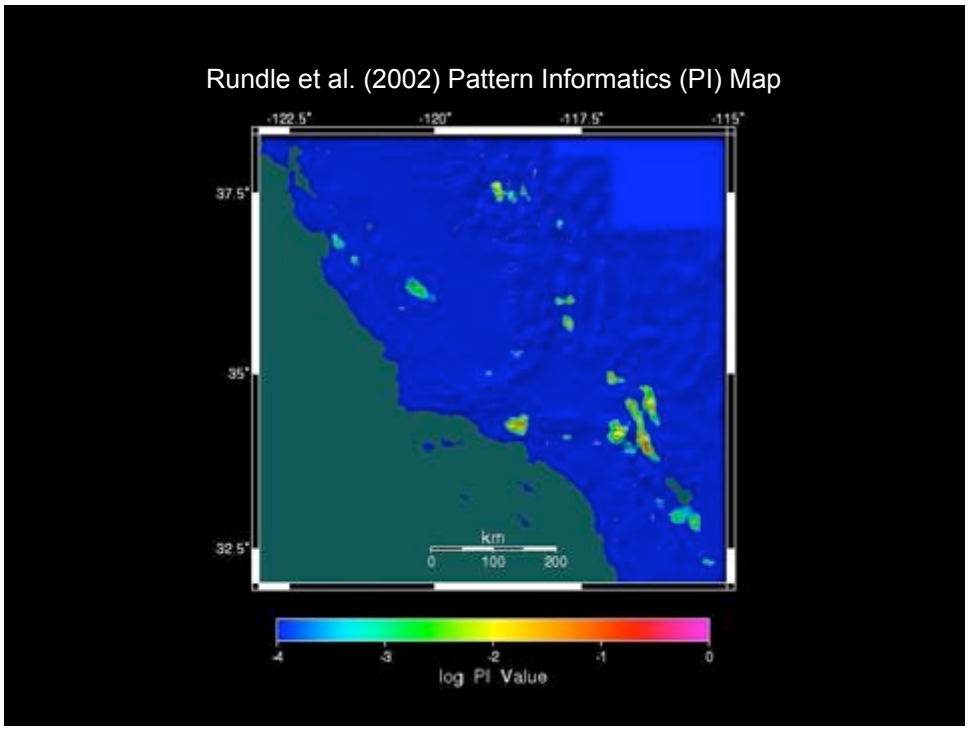
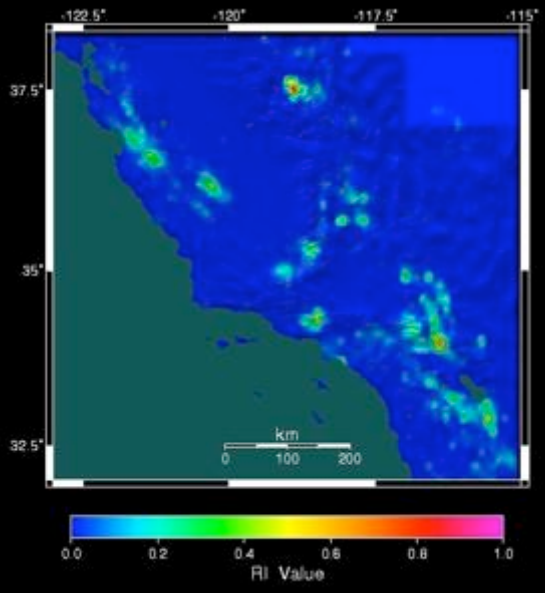
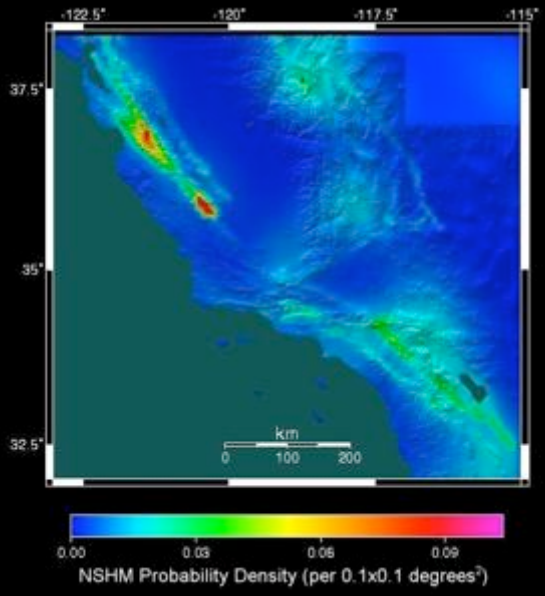
FEATURE
Earthquake Forecast Program Has Amazing Success Rate
10.01.04
"We're nearly batting a thousand, and that's a powerful validation of the promise this forecasting technique holds."


Rundle et al. (2002) Pattern Informatics (PI) Map
-122.5°
-120°
-117.5°
-115°
37.5°
35°
32.5°
km
0
100
200
-4
-3
-2
-1
0
log PI Value

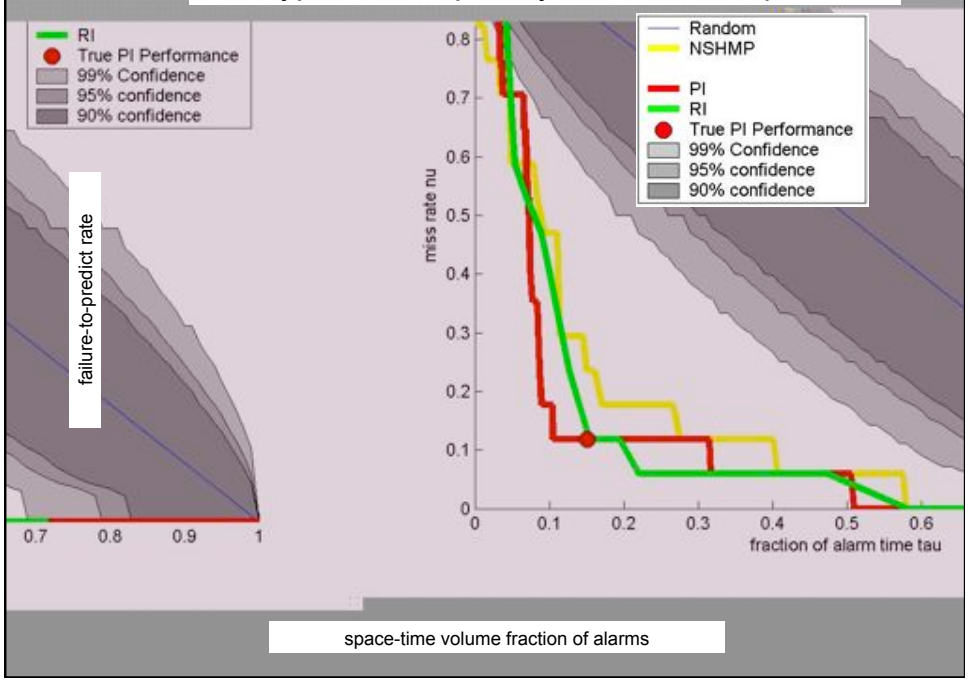
Relative seismic intensity 1932-2000, M ≥ 3 and above



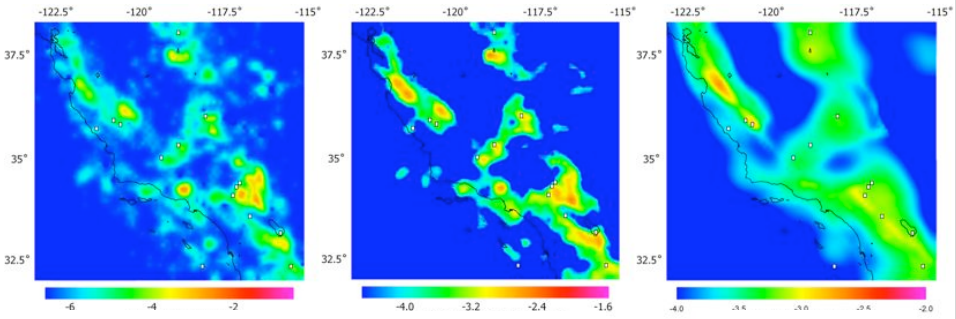
NSHM probability of at least one M ≥ 5 event in a 10 year period



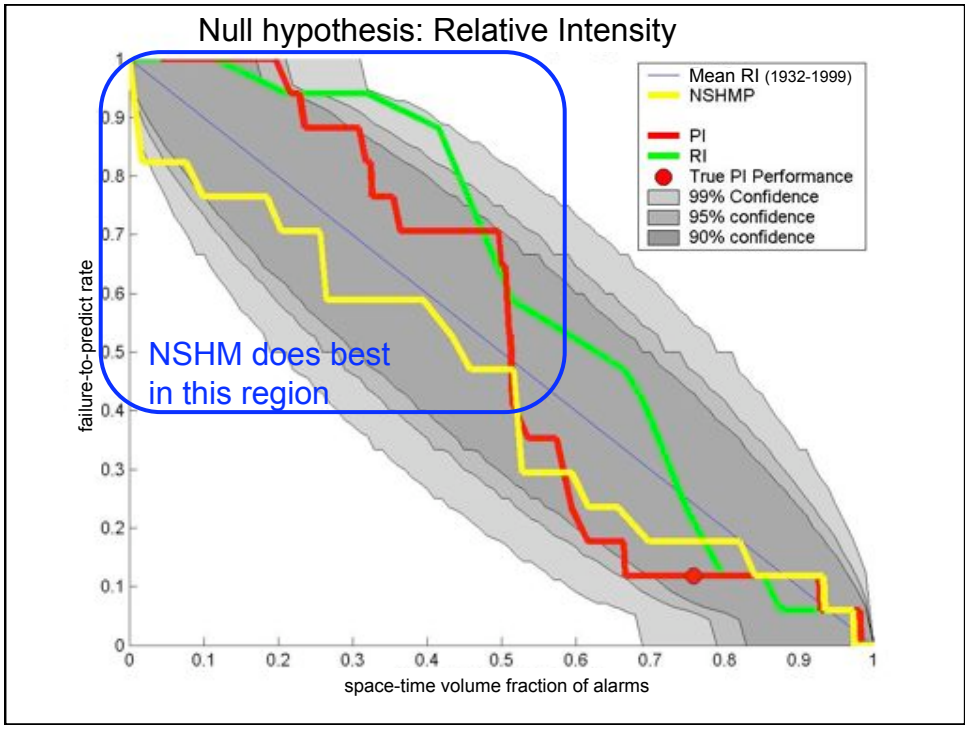
Null hypothesis: Spatially random earthquakes



Testing PI Predictions against RI and the National Seismic Hazard Map



Pattern Informatics | Relative Intensity | National SH Map



Problems in Assessing Predictions

- Scientific publications provide insufficient information for independent evaluation
- Active researchers are constantly tweaking their procedures, which become moving targets
- Difficult to find resources to conduct and evaluate long-term prediction experiments
- Data to evaluate prediction experiments are often improperly specified
- Standards are lacking for testing predictions against reference forecasts

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SCEC Objectives in Prediction Research

- Conduct paleoseismic research on the southern San Andreas and other major faults with emphasis on reconstructing the slip distributions of prehistoric earthquakes, and explore the implications of these data for behavior of the earthquake cycle and time-dependent earthquake forecasting.
- Investigate stress-mediated fault interactions and earthquake triggering and incorporate the findings into time-dependent forecasts for Southern California.
- Establish a controlled environment for the rigorous registration and evaluation of earthquake predictability experiments that includes intercomparisons to evaluate prediction skill.
- Conduct prediction experiments to gain a physical understanding of earthquake predictability on time scales relevant to seismic hazards.

CSEP Objectives

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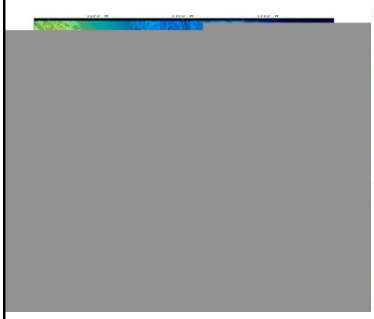
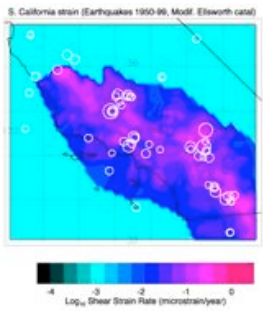
SCEC/USGS Working Group for the Development of

Regional Earthquake Likelihood Models (RELM)



STEP - Seismicity-based
(Wiemer & others)

Fault-Based Simulation
(Ward)



GPS Strain Model
(Jackson & others)

CSEP Goals

G1. Reduce the controversy surrounding earthquake prediction through a collaboratory infrastructure to support a wide range of scientific prediction experiments

G2. Promote rigorous research on earthquake predictability through the SCEC program and its global partnerships

G3. Help the responsible government agencies assess the feasibility of earthquake prediction and the performance of proposed prediction algorithms

CSEP Objectives

O1. Establish rigorous procedures for registering and evaluating prediction experiments

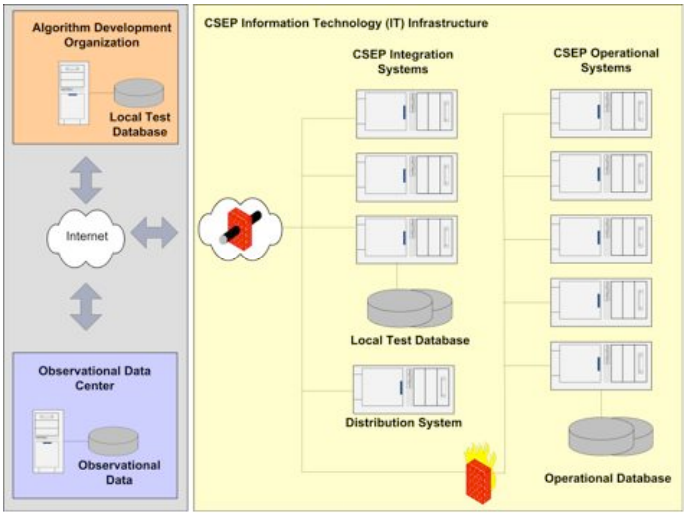
O2. Construct community standards and protocols for comparative testing of predictions

O3. Develop an infrastructure that allows groups of researchers to participate in prediction experiments

O4. Provide access to authorized data sets and monitoring products for calibrating and testing prediction algorithms

O5. Accommodate experiments involving fault systems in different geographic and tectonic environments

CSEP Design



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Measures of Success

M1. Procedures established for all RELM experiments during 1st year and for alarm-based algorithms during 2nd year

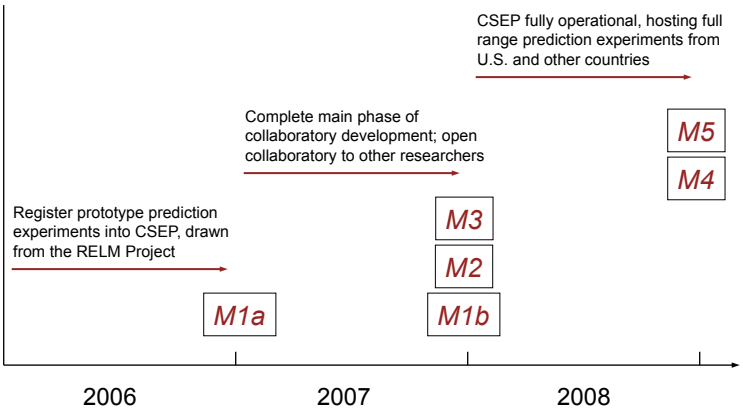
M2. Consensus on testing standards and protocols is endorsed by the agency committees during first 2 years

M3. CSEP is testing prospective prediction experiments, including all RELM experiments, in 2nd year

M4. CSEP is hosting prediction experiments from fault systems outside California in 3rd year

M5. Public communication of CSEP activities is judged to be effective by the SCEC External Advisory Committee and agency committees

Project Timeline



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IT Architect, Philip Maechling, will be CSEP project manager

SCEC Director, Tom Jordan, will lead the project. SCEC BoD will oversee project performance

SCEC Deputy Director, Ralph Archuleta, will integrate CSEP into SCEC research program

CSEP Working Group will develop standards for CSEP design and operations

Focus group on Earthquake Forecasting and Predictability will coordinate scientific prediction experiments

Issues

- Science program
  - New SCEC focus group
- Coordination with government agencies
  - USGS/NEPEC
  - OES/CGS/CEPEC
- Communication with the public
- International collaborations
- Sustainability

End